Lecture 12:
Dark matter searches with long-lived particles

The lifetime of a particle, \( \tau \), is determined by its decay width, \( \Gamma \), as

\[ \tau = \frac{1}{\Gamma} ; \quad \Gamma \sim g^2 \left( \frac{\Delta m}{m} \right)^n m. \]

A particle is called long-lived if all of its decay modes are suppressed, for instance, by:

a) a small coupling \( g \) to other particles
b) a small mass difference \( \Delta m \) with its decay products
c) forbidden decays at tree level.

Many models of dark matter predict long-lived mediators. Examples are:

i) production out of thermal equilibrium

\[ \text{freeze-in: } \begin{array}{c} \ell^- \to g \to z \to \ell^- \\
\end{array} \quad g \approx 10^{-3} \]

ii) thermal freeze-out driven by co-annihilation

\[ \text{co-annihilation: } \begin{array}{c} \tilde{z}^0 \to W^+ \to l^+ \\
\end{array} \quad \Delta m/m \approx 0.1 \]

iii) freeze-out out of chemical equilibrium

\[ \text{co-scattering: } \begin{array}{c} \tilde{z}^0 \to W^+ \to l^+ \\
\end{array} \quad g \approx 10^{-5} \quad \Delta m/m \approx 0.1 \]
How to catch a long-lived particle (LLP)?

A crucial quantity in observing an LLP is its decay length

\[ d = \beta c t = \beta \gamma c \tau. \]

\( t \): time in laboratory frame
\( \tau \): proper time (life time) of LLP
\( \beta \gamma \): Lorentz boost

The number of LLPs remaining at a distance \( L \) from the source decreases exponentially:

\[ \frac{N_L}{N_0} = e^{-L/d}. \]

\( N_L \): particles remaining at \( L \)
\( N_0 \): particles produced at source

For a source that produces LLPs spherically symmetrically, the number of LLPs decaying within the detector volume \( \Delta V = \Delta L^3 \Delta \Omega \) is

\[ N_{\Delta V} \approx N_0 \frac{\Delta \Omega}{4\pi} \left( e^{-\frac{L}{d}} - e^{-\frac{L+\Delta L}{d}} \right); \quad d > L, L + \Delta L. \]

**Example** ATLAS/CMS:
\( \Delta L \sim 10 \text{ m}; \Delta \Omega \sim 4\pi; L \sim 0 \text{ m} \)

\( \beta^+ : c \tau \sim 1 \text{ mm}; \gamma = \frac{E_{\beta^+}}{m_{\beta^+}} = \frac{50 \text{ GeV}}{500 \text{ MeV}} = 10; \beta \approx 1 \rightarrow d \sim 1 \text{ cm} \)

\( \pi^+ : c \tau \sim 1 \text{ mm}; \gamma = \frac{50 \text{ GeV}}{140 \text{ MeV}} \approx 500; \beta \approx 1 \rightarrow d \sim 5 \text{ km} \)
→ B⁺ mesons typically decay within the LHC detectors; π⁺ decay outside.

new LHC far detector FASER:

L ~ 500 m; ΔL ~ 1.5–5 m; radius R ~ 0.1–1 m → ΔS ≲ 4π

FASER will target neutral LLPs with |ΔL| ≳ 100 m, produced at the LHC in the forward direction and decaying into charged particles.

\[ \theta \sim \frac{m_i}{E_\gamma} \sim \mu \text{rad} \]